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5. Early Pleistocene fluvial and estuarine records of climate change in the southern Netherlands and northern Belgium

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1 INTRODUCTION

Current understanding of the Early Pleistocene stratigraphy and climate of the Netherlands and Northwest Europe is essentially based on vegetation changes, largely reconstructed from pollen assemblages, that have been related to changes in climate. In the Netherlands, the Plio/Pleistocene boundary is traditionally placed at c. 2.3 million years BP (Zagwijn, 1989). Suc et al. (1997) proposed to lower the Plio/Pleistocene boundary to the Gauss-Matuyama magnetic reversal at c. 2.6 million years BP. Previously, within the Tiglian Stage, three warm (Tiglian A, Tiglian C3 and Tiglian C5) and two cold substages (Tiglian B, Tiglian C4c) have been recognized in the southeastern Netherlands (Venlo area) (Zagwijn, 1957, 1960, 1963; Westerhoff et al., 1998). According to De Jong (1988) and Zagwijn (1989) the Early Pleistocene glacials were not periods of extreme cold and the climatic oscillations lasted longer and had a lower amplitude than those of the Late Pleistocene. The deep-sea record, however, shows frequent and high-amplitude climatic oscillations (Shackleton et al., 1995) throughout this period and Funnell (1996) correlated the Tiglian Stage of the Netherlands with Oxygen Isotope Stages 63 to 91.

In northern Belgium (Beerse area),within the Early Pleistocene Kempen Formation, a cold phase (Beerse Glacial) coincided with a low sea level and was characterized by fluvial and aeolian sedimentary environments and periglacial structures (frost cracks and cryoturbations) (Dricot, 1961; Paepe & Vanhoorne, 1970; Kasse, 1988, 1993). This cold episode was correlated by Kasse (1988, 1993) with the Tiglian C4c of the type localities of the Tegelen Formation in the Venlo area (Zagwijn, 1963b). Later, Gibbard et al. (1995) described periglacial phenomena possibly of Tiglian C4c age at Öbel in Germany, east of the Venlo area. According to Funnell (1996) the Tiglian C4c corresponds with Oxygen Isotope Stage 68.

The interglacial periods are characterized by thermophilous trees and successive interglacials have previously been differentiated on the basis of their distinctive pollen assemblages (Zagwijn, 1960). The colder climatic intervals are characterized by similar pollen assemblages of pine, birch and herbs and are therefore not suited for stratigraphic reconstructions and correlations. The Early Pleistocene succession of warm and cold intervals has been reconstructed from discontinuous fluvial backswamp and channel-fill deposits at many different sites which are embedded within extensive, mostly pollen-free, sandy deposits.

This article documents a new glacial cycle in the Tiglian and thus demonstrates greater complexity in the terrestrial Early Pleistocene stratigraphy of northwestern Europe. In contrast to the continuous sequences of the deep ocean or lake sediment records, the extent to which the numerous climatic cycles of the Quaternary have been registered in fluvial and estuarine successions in the region is not well known. The presence of erosional hiatuses in the terrestrial Early Pleistocene record is shown and the mechanisms responsible for the incompleteness of the record are discussed. The location of the area at the southern rim of the North Sea Basin makes it a very sensitive region where the effects of external forcing (climate, tectonics) on the fluvial and estuarine environment could be expected to be registered.

The sites that we have studied are located close to the towns of Beerse in northern Belgium and Venlo in the southern Netherlands (Fig. 1). At Beerse the Early Pleistocene succession is exposed in clay pits on the west-east orientated Campine Microcuesta; thick estuarine clay beds were deposited here at the landward margin of the southern North Sea Basin. Due to Middle and Late Pleistocene uplift and preferential erosion, the more resistant clay beds form the present-day higher relief at c. 30 m above sea level (Kasse, 1988).

In the neighbourhood of Venlo the Early Pleistocene succession is exposed in many clay pits on the 'High Terrace' of the Rhine and the type sections of the Tiglian are located nearby at Tegelen (Zagwijn, 1960; Westerhoff & Cleveringa, 1996). During the Early Pleistocene and early Middle Pleistocene predominantly fluvial sequences of the Rhine and the Meuse were deposited. Later, uplift of the area resulted in erosion by the Meuse and terraces were formed at c. 45 m above present sea level.

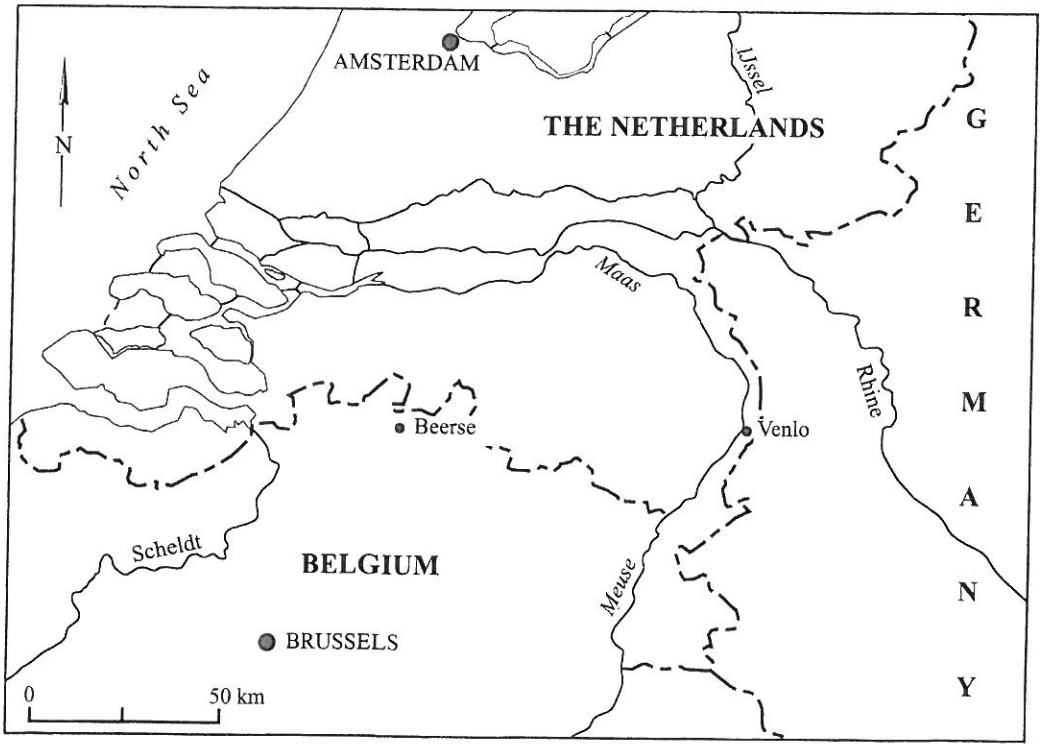


Figure 1. Location map of the sites investigated at Beerse Ossenweg and Venlo Laumans.

2 EARLY PLEISTOCENE LITHOSTRATIGRAPHY AND PALYNOLOGY

2.1 *Beerse*

The clay pits near Beerse in northern Belgium have been studied for several decades (De Ploey, 1961; Dricot, 1961; Paepe & Vanhoorne, 1970, 1976; Kasse, 1988, 1990, 1993, 1996). The Early Pleistocene succession consists of three members: a basal clay unit (Rijkevorsel Member), an intermediate sand unit (Beerse Member) and an upper clay unit (Turnhout Member) (Figs 2, 3 and 4). These three members have been correlated by pollen analysis and magnetostratigraphy with the Tiglian substages C3, C4 and C5 respectively (Kasse, 1988, 1996). The Rijkevorsel Member is a bluish grey non-calcareous clay, sandy and silty at the base, with a clear fining upward tendency towards the top (Fig. 3a: unit 1). It has been interpreted as an estuarine tidal flat and salt marsh deposit (Dricot, 1961; Kasse, 1988). The Beerse Member overlies the lower clay without evidence for erosion. The member consists of fine sand with four distinct soil or peat horizons (Fig. 3a: unit 2). Frost cracks and small ice-wedge casts are common in the sand beds, while the lower three soil and peaty horizons are often strongly involuted (Fig. 5a) (Kasse, 1993). The Beerse Member shows a drying-upwards trend and the Beerse Member has been interpreted in terms of shallow braided rivers giving way upwards to aeolian sand sheets (Fig. 4). The contact with the overlying Turnhout Member has been subject to channel erosion (Fig. 3a: unit 3/5). Over short distances the Beerse Member can be completely preserved (Fig. 3a east side) or completely eroded (Fig. 3a west side). The Turnhout Member consists of a bluish to greenish grey non-calcareous clay with a clear fining upward trend. Heterolithic clay-sand deposits change upwards into stiff, crumbly clay, locally

CHRONOSTRATIGRAPHY			LITHOSTRATIGRAPHY		PROVE-NANCE	CLIMATE
M.PL	Cromerian		Sterksel Formation		R + M	complex
EARLY PLEISTOCENE	Bavelian		Kedichem Formation	Bavel Member	R + M	complex
	Menapian			Gilze Member	S + M	cold
	Waalian				S (+ R)	complex
	Eburonian				S	cold
	Tiglian	C5	Tegelen Formation	Turnhout Member	R (+ S)	complex
		C4		Beerse Member	S	cold
		C3		Rijkevorsel Member	R (+ S)	warm
		B		Hiatus		cold
		A				warm
	Praetiglian		Kiesel-oölite Formation			cold
PLIOCENE				Merksplas Sand		warm

Figure 2. Chrono- and lithostratigraphy of the Early Pleistocene deposits in the southern Netherlands and northern Belgium. R = Rhine, M = Meuse, S = Scheldt.

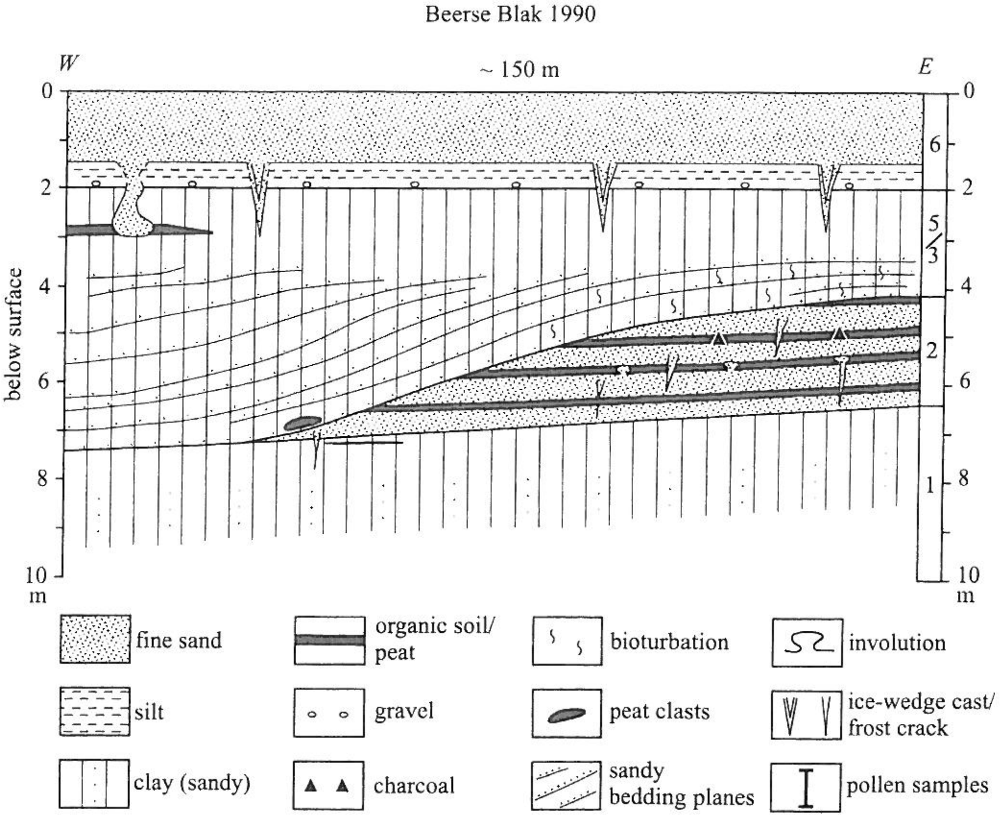


Figure 3a. Generalized section of the exposures at Beerse Blak in 1990. At Beerse Blak the glacial Beerse Member (unit 2) has been severely eroded by the tidal channels of the interglacial Turnhout Member (units 3/5). 1 = Rijkevorsel Member; 2 = Beerse Member; 3/5 = Turnhout Member; 6 = Twente Formation.

with an intercalated peat bed in the upper part. Heterolithic, lenticular and lateral accretion bedding in the deeper channels and bioturbation features are common (Fig. 3a) and the Turnhout Member has been interpreted as a tidal channel, flat and brackish marsh sequence (Dricot, 1961; Kasse, 1988).

The Early Pleistocene sequence is overlain by a Late Pleistocene (Weichselian) unit of aeolian silt and sand (Fig. 3a: unit 6) with large-scale periglacial features. At the transition from the Early to the Late Pleistocene units a gravel lag deposit is present that represents an erosional hiatus, comprising the Middle and part of the Late Pleistocene.

Since 1996 a new clay pit has been worked (Fig. 3b and 4) close to the previously studied Beerse Blak and Merksplas Strafinrichting pits (Kasse, 1988). In general, in comparison to the old pits, only minor differences in the stratigraphic record were observed:

- The Rijkevorsel Member contains two fining upward sequences of silty clay to clay locally with a thin organic bed (c. 10 cm) near the top of the upper fining-up sequence (Fig. 3b: unit 1).
- The lowermost organic soil of the Beerse Member almost directly overlies the Rijkevorsel Member (Figs 3b and 4: unit 2) and a thin intervening sand bed is present only locally between the two.

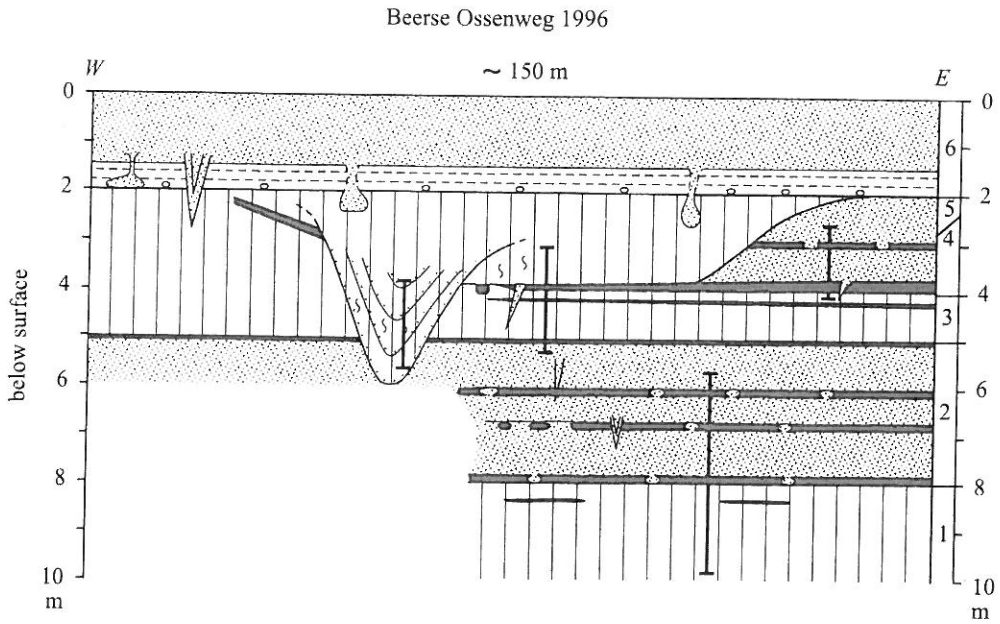


Figure 3b. Generalized section of the exposures at Beerse Ossenweg in 1996. At Beerse Ossenweg the glacial Beerse Member is fully preserved. Within the Turnhout Member a younger glacial sand unit (4) is locally preserved at the east side of the section. 1 = Rijkevorsel Member; 2 = Beerse Member; 3 = base of Turnhout Member; 4 = sand unit intercalated in Turnhout Member; 5 = upper part of Turnhout Member; 6 = Twente Formation.

- The Beerse Member is almost completely preserved, the upper organic bed, that directly overlies a strongly bleached eluvial horizon of a podsol soil, being present over the whole exposure. This means that tidal channel erosion, preceding the deposition of the Turnhout Member, did not occur here.

The Turnhout Member in three of the four pit faces consists of one clay unit without clear fining-upward sequences or lateral accretion bedding characteristic of channel migration (Fig. 3b: units 3 and 5). This indicates that, in comparison to the other pits, low-energy tidal environments prevailed. One of the pit faces showed significant differences to the succession detailed above. The eastern pit face showed a 2 m thick sand layer (Fig. 3b and 4: unit 4) that split the Turnhout Member into two clay units (Fig. 3b: units 3 and 5). The base of sand unit 4 conformably overlies unit 3 of the Turnhout Member. The sand is identical in grain size to the underlying Beerse Member (Fig. 4: unit 2 and 4). It is fine-grained and dominated by slightly deformed horizontal bedding of shallow fluvial or aeolian origin. At the base of the sand unit several (frost) cracks have been found that penetrate the underlying clay of unit 3 (Fig. 5b). The cracks are up to 70 cm deep and 5 cm wide and filled with pale yellow sand of unit 4. Within unit 4 a weakly developed podsol soil was found that was deformed by involutions of c. 30 cm amplitude (Fig. 5c). Sand unit 4 of the Turnhout Member has been preserved only locally (Fig. 3b). Clay unit 5 overlies unit 4 with a clear erosional boundary formed by channel erosion prior to the deposition of unit 5. Surprisingly however, in those cases where unit 4 has been eroded completely the erosional contact between clay units 5 and 3 can hardly be distinguished (Fig. 5b).

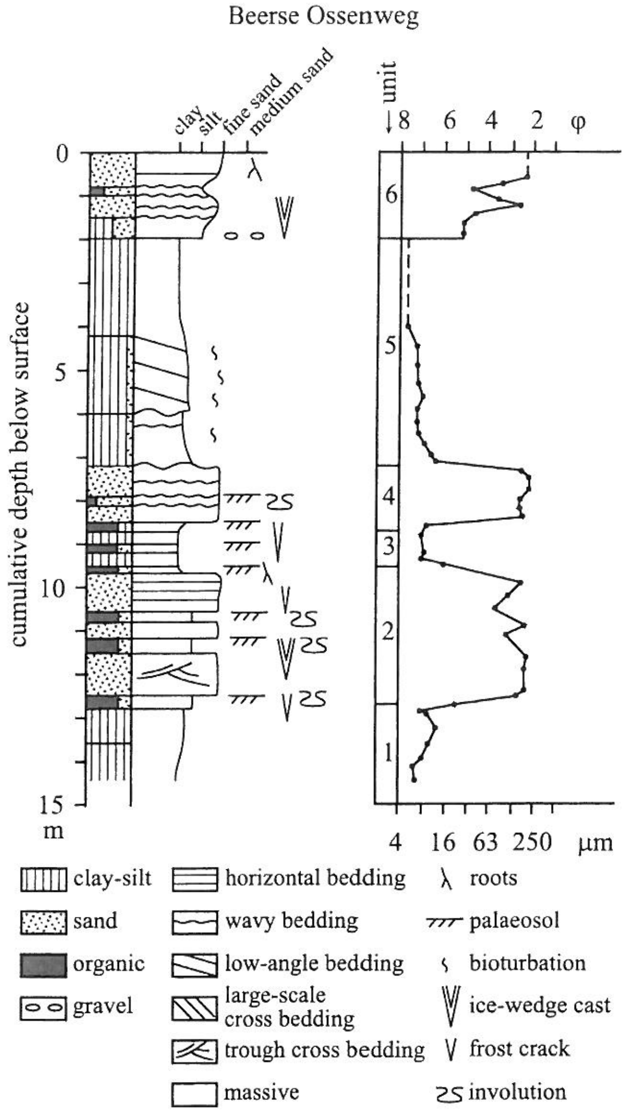


Figure 4. Sedimentological log of exposure Beerse Ossenweg. Note the similarity in grain size of the interglacial units 1, 3, 5 and the glacial units 2 and 4.

Forty samples were taken from the sequence for pollen analysis (Fig. 6) and the pollen sum was c. 200 grains per sample. Five major zones have been distinguished that show a strong correlation with lithofacies.

Zone 1 coincides with the Rijkevorsel Member and contains high amounts of thermophilous trees, especially *Quercus*, *Corylus* and *Alnus*, that point to interglacial conditions. The thermophilous trees show a decrease and the upland herbs a simultaneous increase to the top of the zone. First *Quercus* and *Ulmus* disappear, later followed by *Corylus* and finally by *Alnus*, which can be interpreted as an effect of gradual cooling. The Chenopodiaceae are important in the lower part of zone 1. This family is associated with tidal litter zones or salt marsh environments (Dricot, 1961).

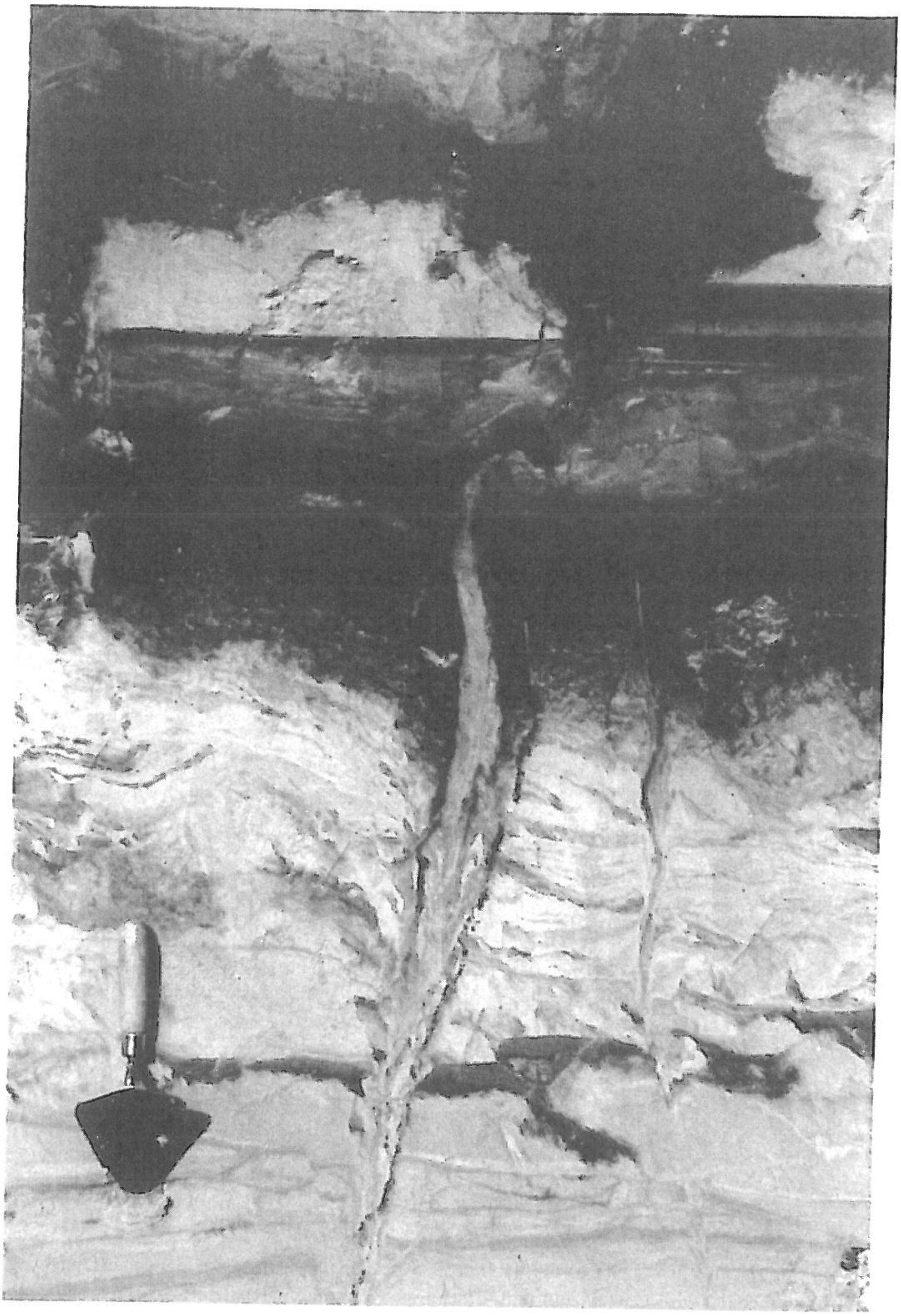


Figure 5a. Periglacial phenomena of the Tiglian C4c glacial phase (unit 2) in Beerse Ossenweg. Small ice-wedge cast in the sands and soils of the Beerse Member (unit 2) indicating permafrost conditions. Trowel for scale is 25 cm.

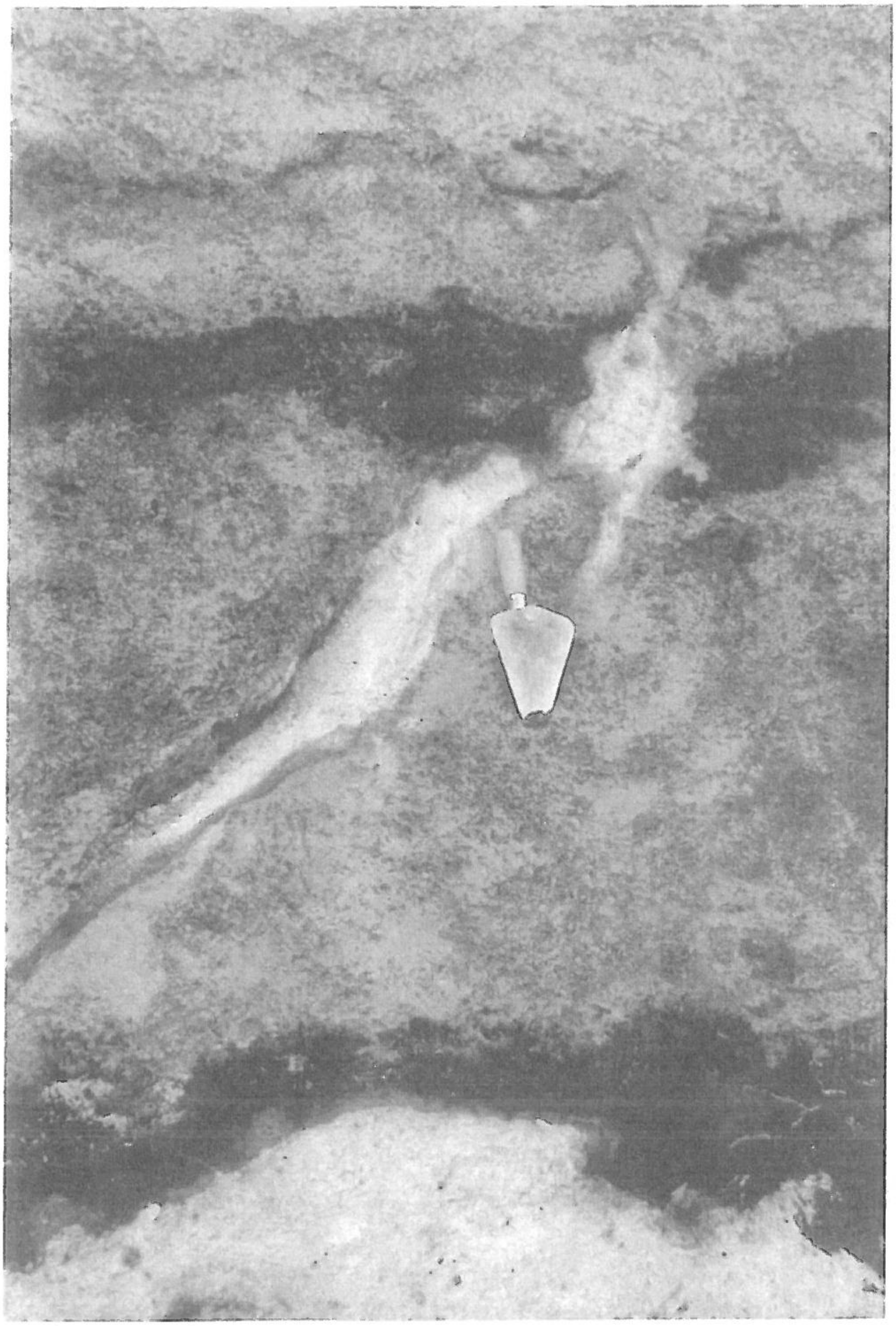


Figure 5b. Periglacial phenomena of the Tiglian C5b glacial phase (unit 4) in Beerse Ossenweg. Frost crack associated with glacial sand unit 4 (see Fig. 3b middle part). The frost crack has penetrated the interglacial clay unit 3 and the sand of unit 4 has been eroded completely here before the deposition of interglacial clay unit 5. Note that the erosional boundary left and right of the crack is hardly visible. At the base of the photo the white sand of the Beerse Member is exposed. Trowel for scale is 25 cm.

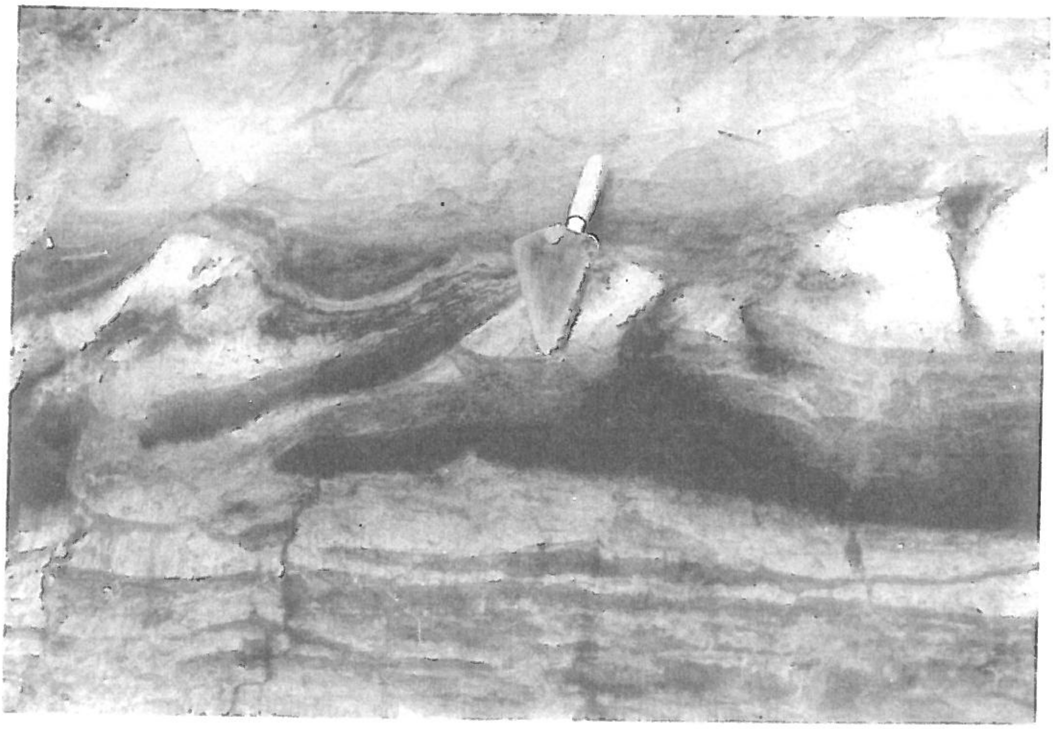


Figure 5c. Periglacial phenomena of the Tiglian C5b glacial phase (unit 4) in Beerse Ossenweg. Cryoturbations of the weakly developed podsolic soil in unit 4. Trowel for scale is 25 cm.

Zone 2 coincides with the Beerse Member, except for the uppermost organic layer of the Beerse Member, which is part of zone 3. The pollen diagram is characterized by a near absence of thermophilons trees. *Betula, Pinus* and *Salix* are the dominant three species but *Pinus* values are below 20% which probably indicates long-distance wind transport (Lotter et al., 1992). The vegetation is dominated by herbs (Gramineae and Cyperaceae). This pollen assemblage indicates glacial conditions with tundra vegetation. The presence of *Artemisia* indicates disturbed and bare soil conditions. The Chenopodiaceae, indicative of near-shore conditions and a high sea level in the previous zone, are almost absent in this zone, suggesting coastal retreat and sea-level fall.

Zone 3 represents the uppermost organic layer of the Beerse Member and the basal clay layer of the Turnhout Member (Fig. 3b: unit 3). The vegetation is strongly dominated by thermophilous trees, especially *Alnus*, indicating interglacial conditions. The highest *Alnus* values coincide with peaty beds at the top of the Beerse Member and intercalated in the clay unit, suggesting that *Alnus* was part of the peat-forming vegetation. The dominance of *Alnus* in the peaty, podsolized soil on top of the Beerse Member shows that the peat layer and the podsol were formed during interglacial times on a sandy surface of the previous Beerse Glacial. The high values of Chenopodiaceae in the clay layer indicate high sea level and near-shore conditions. Two samples from unit 3 were analyzed on the presence of the water-fern *Azolla tegeliensis*, a guide fossil for the Tiglian, but no megasporangia were found.

Zone 4 coincides with the basal organic unit of the newly discovered sand unit (Fig. 3b: unit 4). The sand itself and the intercalated podzolic soil are devoid of pollen. The vegetation

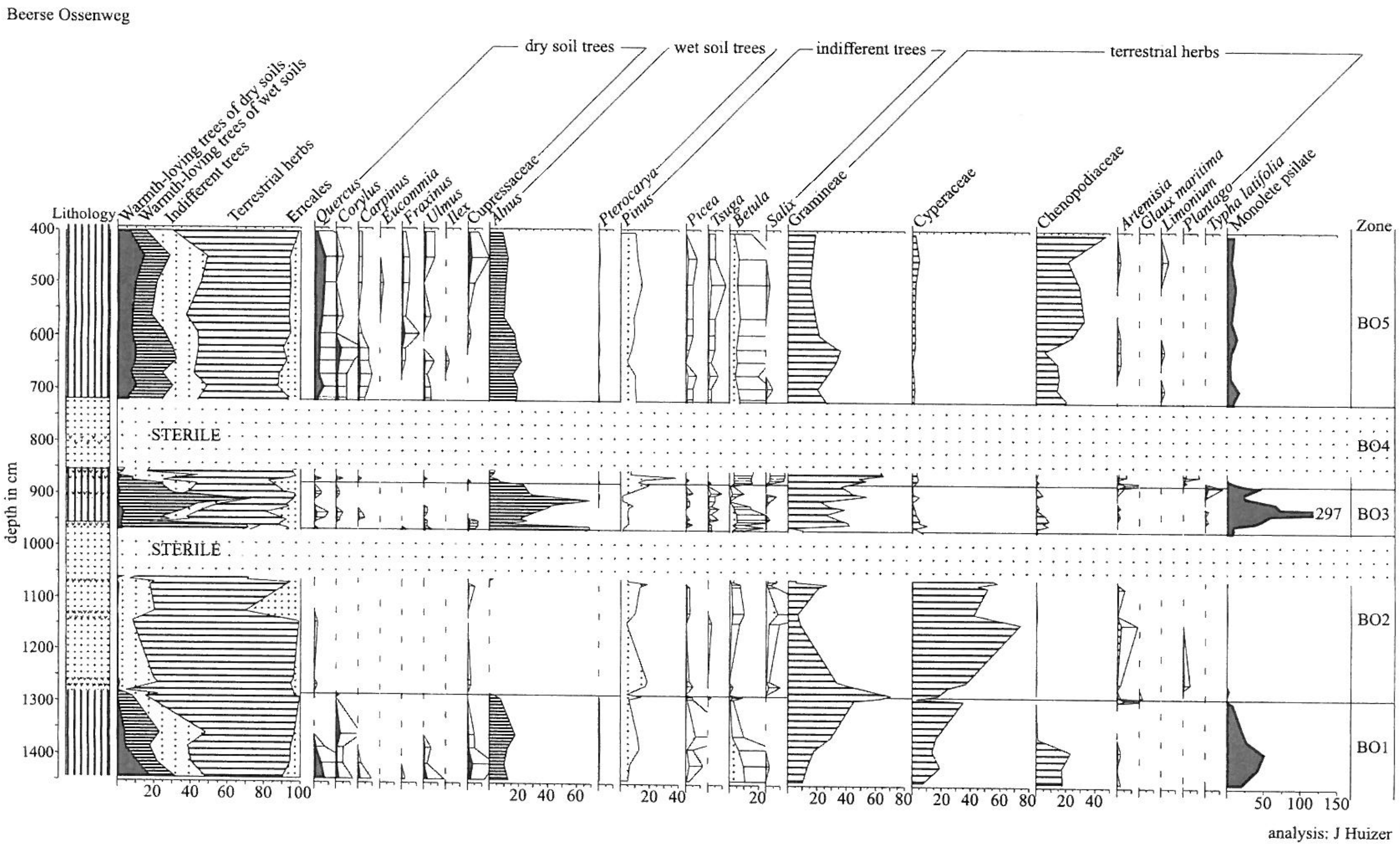


Figure 6. Pollen diagram of Beerse Ossenweg. The clay units are characterized by thermophilous trees and Chenopodiaceae indicating interglacial high sea level conditions; the sand units are characterized by herbs indicating glacial conditions.

is dominated by herbs, especially Gramineae. *Pinus*, *Betula* and *Salix* are the dominant trees. Pinus values up to 35% suggest local presence. *Artemisia* shows a maximum again. Like zone 2, the tundra or taiga vegetation of this zone points to glacial conditions. One megasporangium of *Azolla tegeliensis* was found at the base of unit 4.

Zone 5 coincides with the upper clay bed of the Turnhout Member (Fig. 3b: unit 5). The pollen composition strongly resembles zone 1. Thermophilous trees like *Quercus*, *Corylus*, *Carpinus*, *Fraxinus*, *Ulmus* and *Alnus* are important. In contrast to zone 1, *Tsuga* is a continuous element in the vegetation. The pollen assemblage indicates a warm temperate interglacial climate and the high presence of Chenopodiaceae and *Limonium* points to near-shore tidal flat, litter zone or salt marsh environments during a high sea level stand. Three out of five samples revealed the presence (up to 30 specimens) of megasporangia of *Azolla tegeliensis*.

2.2 *Venlo*

The clay pits in the Venlo area have been studied for more than a century (Zagwijn, 1998). The type sections of the Late Pliocene Reuverian and Early Pleistocene Tiglian stages have been defined here (Zagwijn, 1960). In the Venlo Laumans clay pit the Tegelen, Kedichem and Sterksel Formations of Early and Middle Pleistocene age are exposed (Figs 2, 7 and 8) and have previously been described by Van Straaten (1956) and Westerhoff & Cleveringa (1996).

The base of the pit shows a bluish grey clayey silt fining-upwards into a non-calcareous clay with a clear prismatic structure probably related to desiccation during soil formation (Fig. 7: unit 1, Tegelen Formation). Overlying this a massive clay with large white siderite nodules is present (Fig. 7: unit 1 upper part). Unit 1 can be interpreted as the low-energy upper part of a fluvial sequence, perhaps the uppermost fill of an abandoned channel or a back swamp deposit. The top of the clay in horizontal sections showed a large-scale polygonal network of wedges, of uncertain depths, filled with fine sand probably derived from unit 2 (Fig. 9a). The boundary between clay unit 1 and sand unit 2 is gradual (coarsening-upward sequence), suggesting continuous sedimentation.

Unit 2 (Kedichem Formation) is present only very locally in the pit because strong channel erosion preceded the deposition of coarse-grained unit 3 (Sterksel Formation) (Fig. 7). Unit 2 predominantly consists of fine-grained sand (Fig. 8). The low-angle trough cross bedding indicates shallow fluvial deposition and a current direction to the northwest. Some loamy beds indicate local low-energy conditions on a flood plain. Unit 2 is divided into two subunits by a humic layer. The absence of sedimentary structures and the presence of root traces indicate soil formation. In the lower part of unit 2, underlying the soil, periglacial phenomena are frequently found (Figs 7, 8 and 9). Involutions with an amplitude of 50 cm are very well developed with clear flat-bottomed bases (Fig. 9b) and thermal contraction cracks are common. In one case a poorly developed ice-wedge cast was found. In the upper part of unit 2, overlying the soil, periglacial phenomena are less frequent (Fig. 7). The soil has been penetrated by widely spaced, deformed wedge structures or involutions, some 70 cm deep, filled with white sand (Fig. 9c).

Unit 3 (Sterksel Formation) consists of coarse-grained gravelly sands (Figs 7 and 8) of the so-called High Terrace in this area. The base shows channel forms and lag deposits and large-scale planar cross bedding is dominant indicating straight-crested bars migrating in a braided river. Current direction is towards the northwest. Locally, fine-grained sands

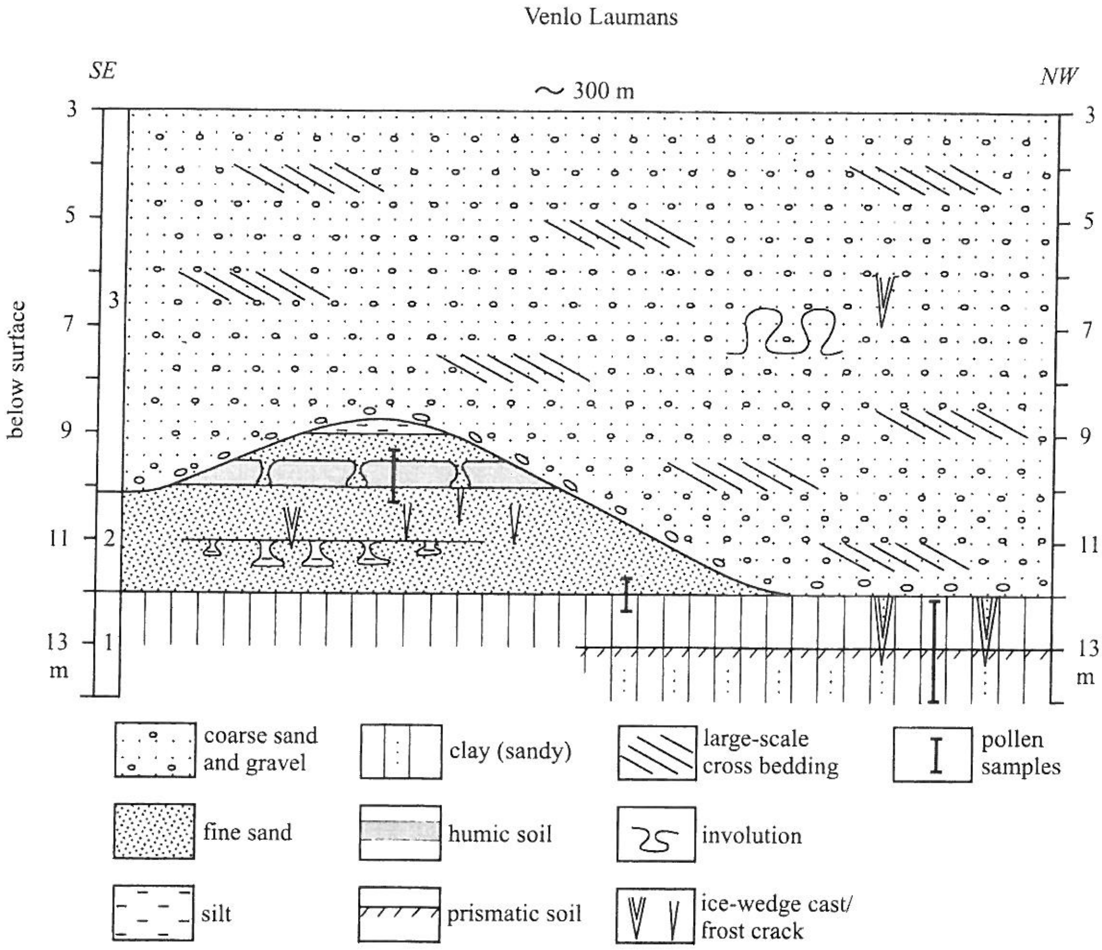


Figure 7. Generalized section of exposure Venlo Laumans. The Kedichem Formation (unit 2) is only locally preserved due to intense erosion prior to the deposition of the Sterksel Formation (unit 3). 1 = Tegelen Formation.

are present with major involutions up to one metre thick. An isolated ice-wedge cast was observed higher in the sequence.

Samples were taken for pollen analysis from units 1 and 2, but the lower part of clay unit 1 and the soil of unit 2 appeared to be poor in pollen. Pollen was recovered from the upper part of clay unit 1 and the coarsening-upward transition to unit 2 (Figs 7 and 10). Three pollen zones have been distinguished:

- Zone 1 is characterized by the presence of thermophilous trees of dry and wet soils, especially *Quercus*, *Corylus* and *Alnus*, but the values do not exceed 20%. Gramineae and Cyperaceae dominate the herb vegetation. *Typha latifolia* is present only in this zone.
- Zone 2 is dominated by *Pinus* and thermophilous trees have decreased.
- In zone 3 the values of the thermophilous trees are low. *Quercus*, *Ulmus*, *Pterocarya* and *Carya* have disappeared while *Corylus* and *Alnus* are still present. The Ericales show a strong increase at the start of this zone. *Artemisia*, *Plantago* and *Saxifraga* are present indicating an open vegetation cover.

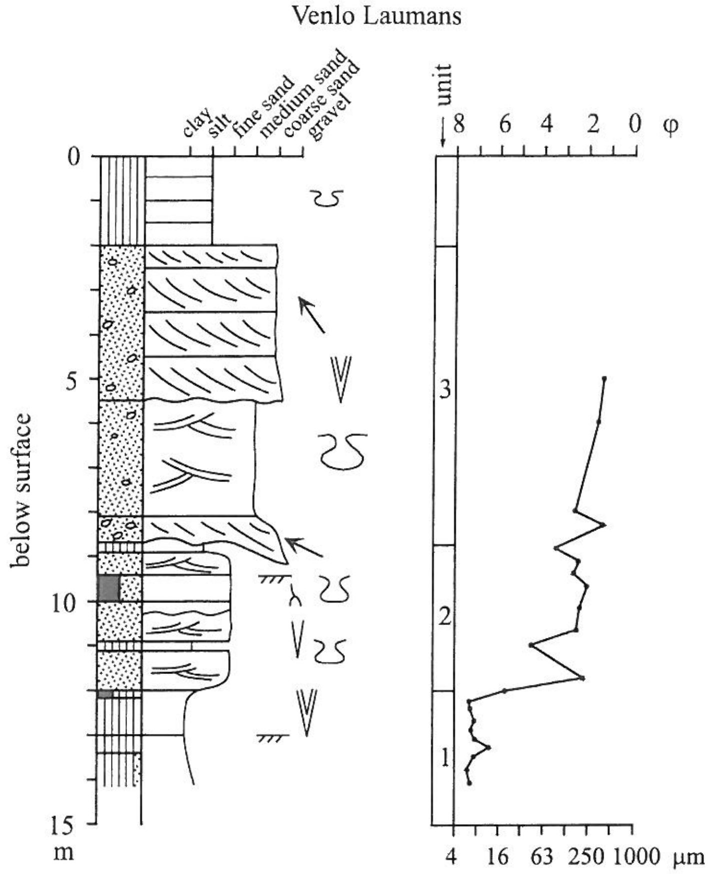


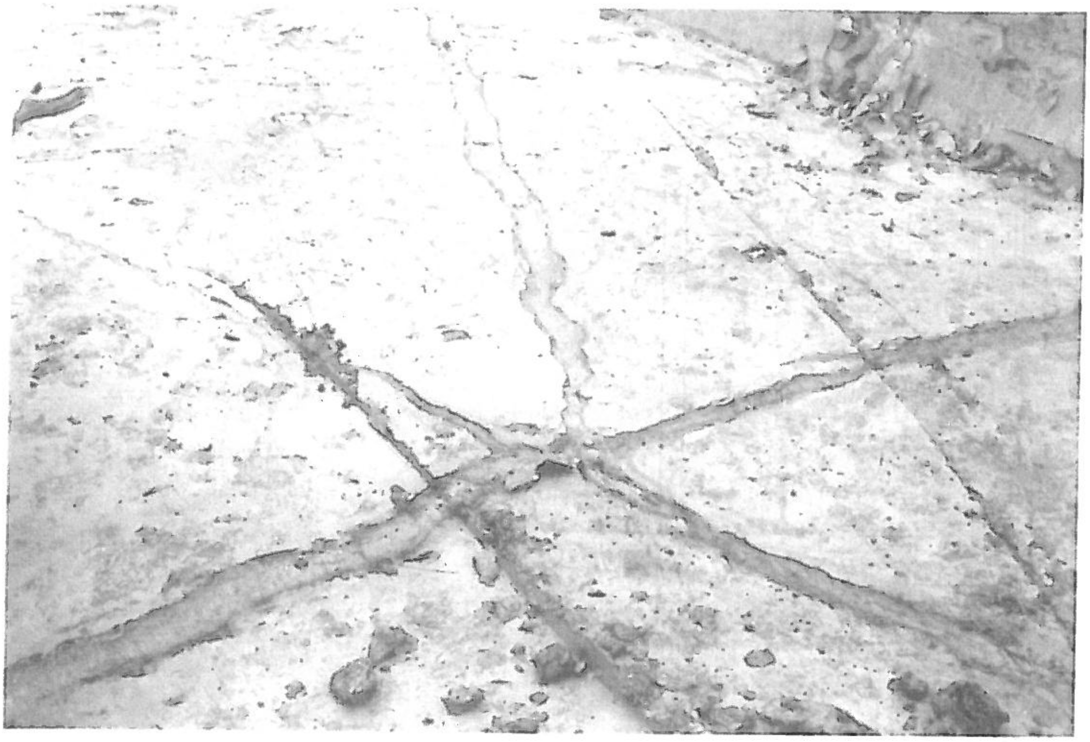
Figure 8. Sedimentological log of exposure Venlo Laumans. The clay of the Tegelen Formation (unit 1) is gradually overlain by fine sands of the Kedichem Formation (unit 2) with many periglacial features. See Figure 4 for legend.

3 DISCUSSION

3.1 *Early Pleistocene stratigraphy*

Previously, within the Tiglian complex, three warm (Tiglian A, Tiglian C3 and Tiglian C5) and two cold intervals (Tiglian B, Tiglian C4c) have been distinguished (Zagwijn, 1960, 1963) (Fig. 11). The Rijkevorsel and Turnhout Members in northern Belgium have been attributed to the Tiglian C3 and C5 respectively because of the interglacial character of the vegetation, the absence of *Fagus* (common in the Tiglian A in the Netherlands (Zagwijn, 1963b; Westerhoff et al., 1998)) and the presence of *Azolla tegeliensis* (Greguss & Vanhoorne, 1961; Kasse, 1988, 1993). The Beerse Member, intercalated between the Rijkevorsel and Turnhout Members, was associated with the Tiglian C4(c) glacial phase, because of its glacial pollen assemblage and periglacial structures (Kasse, 1993).

Our new results show, above the Beerse Glacial (Fig. 6: zone 2) attributed to the Tiglian C4c, a further episode of cold (Fig. 6: zone 4) that is characterized also by a low sea level, fluvial and aeolian sand deposition, cryogenic structures and cold vegetation with mainly *Pinus*, *Betula*, *Salix* and herbs. The sandy sediments of this latter cold phase are



a)

b)

Figure 9a and 9b. Periglacial phenomena of the Eburonian glacial phase (unit 2) in Venlo Laumans. Trowel for scale is 25 cm. (a) Horizontal section with polygonal wedge pattern in the top of clay unit 1 filled with sand of unit 2 indicating permafrost conditions at the start of the Eburonian. (b) Large-scale cryoturbations in the lower part of unit 2 attributed to the Eburonian glacial.

c)

Figure 9c. Periglacial phenomena of the Menapian glacial phase (unit 2) in Venlo Laumans. Deformed involutions of Menapian age with white sand disturbing the Waalian soil. Trowel for scale is 25 cm.

Venlo Laumans

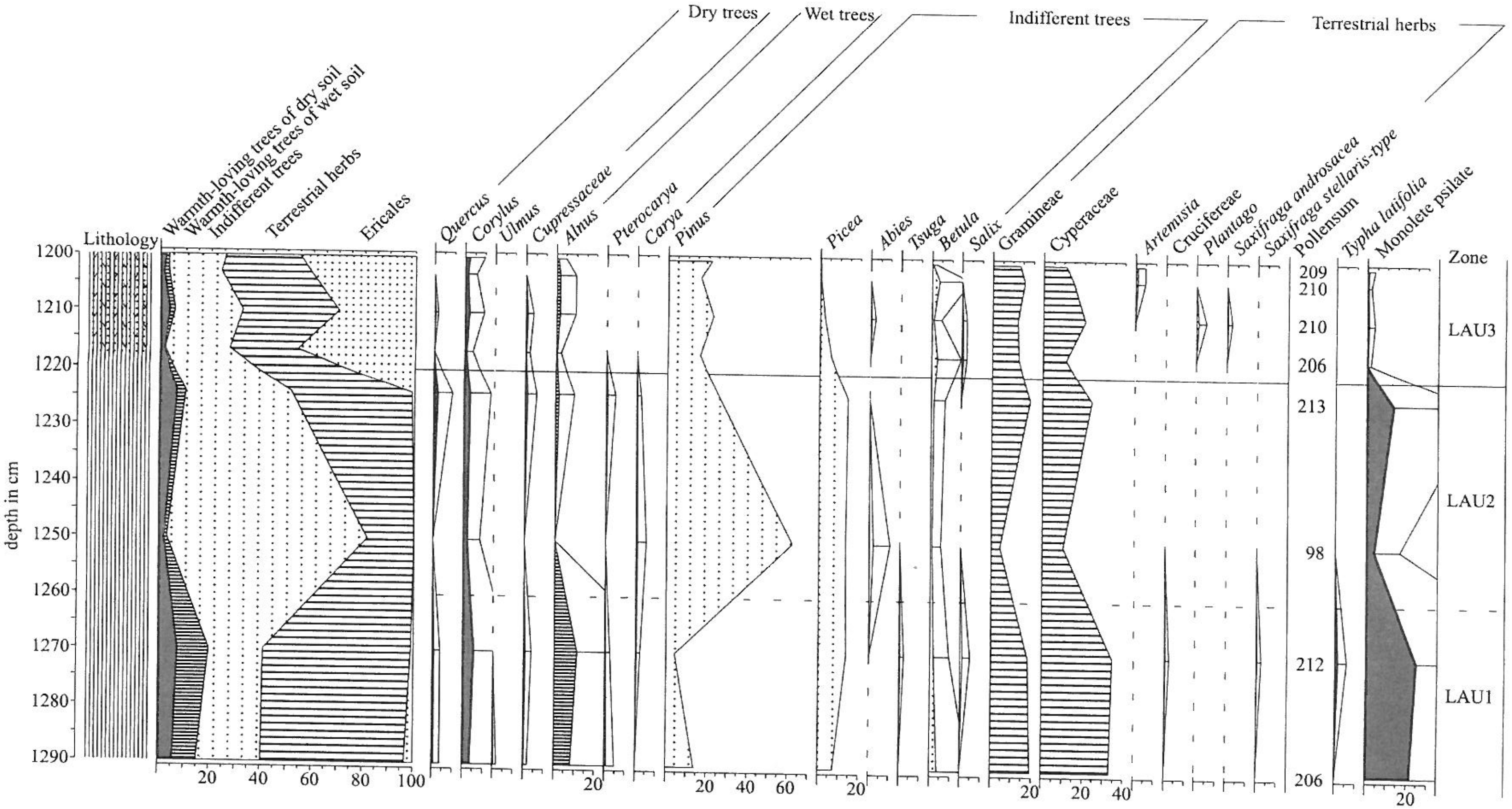


Figure 10. Pollen diagram of the transition from clay (unit 1) to sand (unit 2) in Venlo Laumans. The decrease in thermophilous trees and increase in herbs reflect the climatic cooling at the Tiglian – Eburonian boundary.

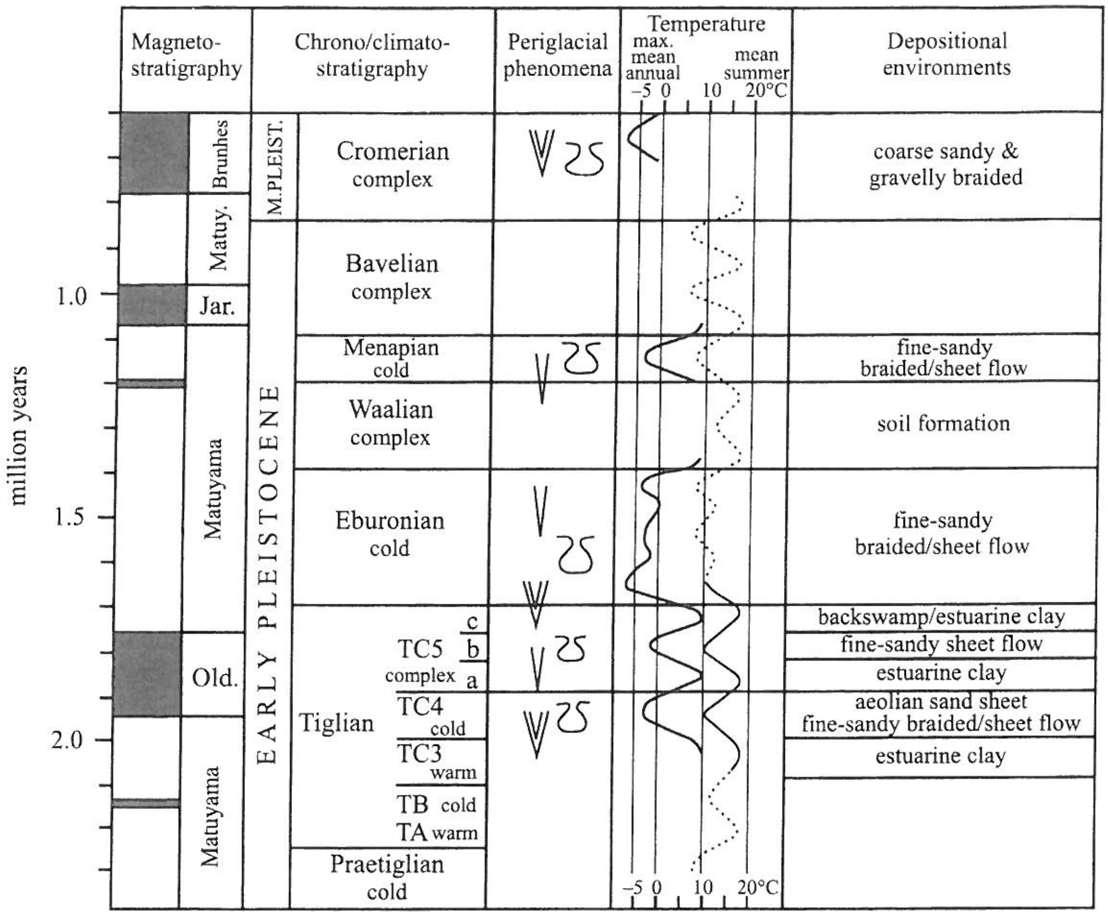


Figure 11. Synthesis of Early Pleistocene climatic evolution in the region. The glacial – interglacial temperature cycles reveal both high frequency and amplitude. Changes in depositional environment are often related to climate change. Magnetostratigraphy according to Cande & Kent (1995); chrono/climatostratigraphy according to Zagwijn (1989), Kasse (1988, 1993) and this study; periglacial phenomena according to this study; maximum mean annual temperature according to this study; mean summer temperature according to Zagwijn (1963, 1989) (dotted line) and this study (continuous line); depositional environments according to this study.

intercalated in the clayey Turnhout Member of Tiglian C5 age. This means that the Tiglian C5, previously defined as one undivided warm temperate phase, is a climatic complex of at least two interglacials (TC5a and TC5c, Fig. 6: zones 3 and 5) and one glacial. For the time being this new glacial phase (Fig. 6: zone 4) will be referred to as the intra-Tiglian C5 glacial (TC5b) (Fig. 11).

The results show that both the Tiglian glacials (Beerse Glacial or Tiglian C4c and new intra-Tiglian C5 glacial) are dominated by *Pinus*, *Betula*, *Salix*, Gramineae, Cyperaceae, Ericaceae, *Artemisia* and *Plantago* indicating a tundra or taiga vegetation (Fig. 6: zones 2 and 4). The Tiglian interglacials (Tiglian C3 and C5a and C5c) are characterized by deciduous trees (*Quercus*, *Corylus*, *Carpinus*, *Fraxinus*, *Ulmus* and *Alnus*) of warm temperate climates (Fig. 6: zones 1, 3, and 5). The pollen assemblages of the warm intervals resemble each other strongly. The major difference between the interglacial pollen assemblages is the higher *Alnus* content in pollen zone 3 (Fig. 6), though this seems to be due to the local presence of *Alnus* stands during the formation of the peaty beds. Similarly, high *Alnus* values have been reported from the upper part of the Turnhout Member (Kasse, 1988) which means that the high *Alnus* values can not be used as a characteristic of one specific period. The absence of *Tsuga* in the Rijkevorsel Member and its presence in the Turnhout Member may, on the other hand, reflect a real difference in vegetation during the successive interglacials.

It is concluded that some of the Early Pleistocene interglacials can be differentiated by their specific pollen assemblages, but the recent investigations reveal that more glacial and interglacial phases of the Tiglian Stage have been registered in the terrestrial succession of northwestern Europe. It is likely that these different interglacials have been grouped previously as one interglacial period, because of their lithological and palynological similarity (Figs 4 and 6). The point is that the sea-level low-stand sediments of the cold phases are only very locally preserved at the southern rim of the North Sea basin (Figs. 3a and 3b). The sandy sediments of the glacial phases are frequently eroded by estuarine channels during the subsequent interglacial sea-level high stand. As a result the clay units of the successive interglacials are stacked upon each other, separated only by unconformable contacts that are often difficult to identify. For instance in Fig. 3a (west exposure) only one thick interglacial clay unit seems to be present, while the recent results (Fig. 3b) demonstrate that at least three clay units of three interglacials occur. The clay units (see Fig. 4: units 1, 3 and 5) have the same lithological and environmental characteristics. This indicates that while hiatuses in the Early Pleistocene terrestrial record are very important, their recognition is often problematic. Furthermore, the clay beds at Beerse probably represent only the full- and late-interglacial conditions with a high sea level. The early interglacial periods with rising sea level have not been recorded here.

The results presented above demonstrate greater complexity for the terrestrial successions of the Tiglian Stage. In accordance with the deep-sea record, the duration of the glacial-interglacial cycles was short, although it is important to point out that individual glacials and interglacials are difficult to distinguish as they lack diagnostic characteristics.

3.2 *Temperature reconstructions*

Palaeotemperatures, especially the mean annual air temperature and mean temperature of the coldest month (winter temperature in this paper) can be estimated from the various periglacial structures (Figs 5 and 9) (cf. Maarleveld, 1976; Vandenberghe & Kasse, 1989; Vandenberghe & Pissart, 1993). In combination with the mean temperature of the warmest month (summer temperature in this paper), derived from the palaeobotanical record (cf. Zagwijn, 1963), the amplitude of the climatic oscillations on land can be reconstructed (Fig. 11). Frost cracks are normally associated with a mean annual air temperature lower than –1°C and ice-wedge casts indicate a mean annual air temperature lower than –6°C and a mean temperature of the coldest month lower than –20°C.

The Beerse Member of Tiglian C4c age at Beerse Ossenweg (Figs 3 and 4: unit 2) contains abundant frost cracks but ice-wedge casts are rare (Fig. 5a) and therefore a mean annual air temperature between –1 to –6°C is postulated (Fig. 11) (Kasse, 1993). The deposits of the new glacial phase in the Tiglian C5 (TC5b) (Figs 3 and 4: unit 4) include frost cracks and small cryoturbations (Fig. 5b and 5c) so a mean annual air temperature lower than –1°C is reconstructed. The tundra to taiga vegetation of the TC4c and TC5b glacials shows that the mean summer temperature was around or below 10°C. The combination of the mean annual air temperature (–1 to –6°C) and the mean summer temperature (10°C) indicates a mean winter temperature lower than –12°C and possibly lower than –22°C.

The clay units in Beerse Ossenweg show interglacial pollen assemblages (Fig. 6). According to Zagwijn (1963b), the presence of *Eucommia* indicates a mean summer temperature of c. 18°C. The presence of *Ilex*, a frost susceptible species, has been related to mean winter temperatures higher than –1°C (Iversen, 1944). Combining these summer and winter temperatures results in an estimate of the mean annual air temperature of around 8.5°C, which is comparable to the present day mean annual temperature of the Netherlands and northern Belgium.

The three pollen zones in Venlo Laumans suggest a climatic cooling at the end of an interglacial (Fig. 10). The thermophilous trees of zone 1 indicate the deciduous forest vegetation of an interglacial period. *Typha latifolia* points to a mean July temperature higher than 13°C. In zone 2 the thermophilous elements have decreased and are replaced by a pine forest vegetation. Finally, a more open vegetation established dominated by Ericales, *Artemisia* and other herbs (zone 3) indicating a drop of the summer temperature to c. 10°C or lower. The clay layer is part of the Tegelen Formation and its upper part is attributed in nearby pits to the Tiglian – Eburonian transition (Zagwijn, 1963b: Russel-Tiglia-Egypte pit). Therefore, the interglacial to glacial transition at Laumans is correlated with the late Tiglian – Eburonian boundary (Westerhoff & Cleveringa, 1996).

Within the Laumans pit a prominent soil has been found in unit 2 (Kedichem Formation) (Figs 7 and 8). A similar soil has been described previously from nearby pits and attributed on palynological grounds to the warm temperate Waalian interglacial (Zagwijn, 1960, p. 49 and 57). This means that the sand underlying and overlying the assumed Waalian soil (Figs 7 and 8: unit 2) can be attributed to the Eburonian and Menapian cold stages respectively. Periglacial phenomena in the Kedichem Formation have been recorded previously by Van Straaten (1956), Kortenbout van der Sluijs (1956) and Westerhoff & Cleveringa (1996). The large-scale wedge structures and polygons that formed in the top of clay unit 1 in Laumans (Fig. 9a) indicate very cold conditions, with mean annual air temperatures below –6°C and a mean winter temperature below –20°C at the beginning of the Eburonian glacial phase (Fig. 11). Above this level, but still below the Waalian soil, frost cracks and involutions are common (Fig. 9b), but only one indistinct ice-wedge cast has been found, which suggests somewhat higher mean annual air temperatures (between –1 and –6°C) than at the beginning of the Eburonian glacial.

The assumed Waalian soil has been disturbed locally by large-scale deformed wedges or involutions (Fig. 9c) which penetrate the soil and are filled with white sand from above. This means that their formation is younger than the Waalian and they probably date from the Menapian. A mean annual air temperature lower than –1°C has been postulated for such solitary forms (Vandenberghe, 1988).

The upper coarse-grained unit 3 at Laumans can be correlated with the Sterksel Formation of Cromerian age (Zagwijn, 1960). Locally within the sequence large-scale involutions and one ice-wedge cast have been seen which indicates that the mean annual air temperature was below –6°C during part of the Middle Pleistocene Cromerian Complex (Fig. 11).

Temperature reconstructions of the Early Pleistocene thus show large-amplitude climatic oscillations. Glacials phases had a mean annual air temperature below –1°C and occasionally below –6°C. The interglacials had temperature values comparable to the present day. The amplitude of these Early Pleistocene climatic oscillations was therefore comparable with those of the Late Pleistocene (Vandenberghe, 1992).

3.3 *Climate change and depositional environments*

The results show that there is a clear relationship between climate and depositional environment in these successions. In Beerse Ossenweg, the interglacials were characterized by clay deposition (Figs 3b and 4: units 1, 3 and 5). The sedimentary structures (heterolithic bedding, bioturbation) and the pollen assemblages (Chenopodiaceae, *Limonium*) indicate tidal channel, flat and salt marsh environments and a high sea level. During these high sea-level stands the area in northern Belgium was situated at the southernmost rim of marine deposition along the North Sea Basin. During the glacial phases shallow fluvial and aeolian sand sheet environments were dominant in the Beerse area (Fig. 3b and 4: units 2 and 4). The periglacial phenomena and pollen assemblages indicate cold conditions. The strong correlation between lithological changes and vegetational changes indicates that the alternation of clay and sand deposition was climatically-controlled and sea level related. During the glacial phases a fall in sea level occurred, the estuarine environment regressed and shallow fluvial systems extended their courses to the north. An associated change in sedimentary provenance also took place (Kasse, 1990). During subsequent interglacial phases, transgressions occurred and estuarine environments were established. Marked erosion by laterally migrating tidal channels took place and the sand unit of the previous glacial sea-level low stand was almost completely removed (Fig 3a: unit 2; Fig. 3b: unit 4). As a consequence, stacking of the interglacial estuarine deposits took place, separated by major, but almost indiscernible hiatuses. The preservation of the high-stand deposits is surprising as one would expect erosion during the low stands. It is suggested that, despite the sea level fall, the gradients of the rivers flowing into the shallow North Sea Basin did not change and, in addition, sediment supply increased leading to deposition in stead of erosion.

Farther upstream in the southeastern Netherlands (Venlo Laumans) clay deposition predominantly occurred during the late Tiglian interglacial in a low-energy, probably meandering fluvial system (Figs 7 and 8: unit 1). During the Eburonian and Menapian glacial phases (as reconstructed from the periglacial structures), sand deposition dominated by shallow braided systems (Figs 7 and 8: unit 2). The lithological change from clay to sand (coarsening upward) coincides with a change in vegetation from deciduous forest to tundra (Fig. 10). Thus climatic change is reflected by the vegetation, by periglacial phenomena and by a change in depositional environment. The climate-related change in fluvial style probably resulted from changes in discharge regime and sediment supply as shown by Kasse et al. (1995) for Late Pleistocene rivers. The climatic cooling at the Tiglian – Eburonian transition created a more open vegetation cover and hence increased sediment supply from hillslopes to river channels. The deep seasonal frost or permafrost of the Eburonian glacial period would have created a snow-melt related discharge regime. Both the increased sediment supply and more peaked discharge are responsible for the change in fluvial style and the relative lack of erosion of interglacial deposits, despite the lower base level.

4 CONCLUSIONS

1. The Early Pleistocene terrestrial record of the southern Netherlands and northern Belgium does not preserve a continuous record and hiatuses are common. In northern Belgium, periglacial sandy deposits formed during periods of low sea level were intensively eroded by tidal channeling during the subsequent interglacial high sea level

periods. This resulted in the stacking of interglacial units, separated by hardly distinguishable erosional contacts. In the more upstream fluviatile environments of the southeastern Netherlands, deposition during the interglacials was restricted to back swamp areas and abandoned channels of meandering rivers.

2. The Early Pleistocene record contains more preserved glacial and interglacial phases than previously recognised. In the Beerse area, a new glacial phase has been found in the late Tiglian, younger than the Beerse Glacial of Tiglian C4c age. This new glacial phase, separating two interglacials, has provisionally been assigned the term Tiglian C5b. This means that at least three interglacials and two glacials occurred in the Beerse area during the Tiglian C substage.
3. Early Pleistocene interglacials often have no or few diagnostic features and often cannot be distinguished from each other. The pollen assemblage, grain size and provenance of the successive interglacial deposits resemble each other. The same holds true for the glacials.
4. Changes in depositional environments are controlled by climate change and related sea-level fluctuations. In northern Belgium, predominantly clay deposition occurred in tidal channels, mud flats and marshes (Rijkevorsel Member and two clay units of the Turnhout Member) during three interglacial periods with high sea levels (Tiglian C3, C5a and C5c). Sand deposition occurred by shallow braided systems and aeolian sand sheets (Beerse Member and sand unit in Turnhout Member) during two glacial periods with low sea level (Tiglian C4c and C5b). The alternation of clay and sand units in the Beerse area is climate and sea-level controlled as indicated by vegetation reconstruction and periglacial phenomena. In the Venlo area, the change from low-energy fluvial clay deposition to shallow braided sand deposition coincides with a change from Tiglian interglacial to Eburonian glacial conditions as shown by the vegetation change and periglacial structures.
5. The Early Pleistocene climatic oscillations have a large amplitude, comparable with those of the Late Pleistocene. The deciduous vegetation of the interglacials indicates that the mean summer temperature was around 18°C, the mean winter temperature above –1°C and the mean annual temperature circa 8.5°C. The tundra to taiga vegetation of the glacials shows that the mean summer temperature was around 10°C. The periglacial phenomena (large-scale cryoturbations, abundant frost cracks and some ice-wedge casts) point to deep seasonal frost or permafrost. They show that the mean annual temperature during the glacials was at least lower than –1°C and sometimes lower than –6°C. The mean winter temperature was occasionally lower than –20°C. The start of the Eburonian glacial was extremely cold with continuous permafrost as indicated by large-scale wedge structures and polygons.

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